Section 6.0
Cost Assessment

6.1 Cost Performance

Phytoextraction can be broken into three tasks: crop production, extraction amendment addition, and harvesting. The costs shown below are based on treating an area equal to one acre using a corn crop. The quantities of amendment are based on laboratory studies and knowledge gained from the field demonstration at TCAAP. The costs associated with producing and harvesting the corn crop are shown in Table 6-1. The costs for purchasing, mixing, transporting, and applying the extraction amendments are shown in Table 6-2. The costs for the irrigation system used to water the crop and apply extraction amendments are shown in Table 6-3.

Total cost for using phytoextraction to remediate one acre is $42,145 per crop (Table 6-4). This includes a managing contractor fee of 20% of the direct costs. Assuming that the process treats the top 12 inches of soil, the cost for remediation is equivalent to $26.13 per cubic yard per crop based on an initial soil lead concentration of 1500 mg/kg and a remediation target of 1000 mg/kg. The remediation would require 27 crops over a period of 14 years for a total cost of $706 per cubic yard. To remediate from 1200 mg/kg to 1000 mg/kg would require 11 crops over a six year period, at an approximate cost of $287 per cubic yard.

Reagent costs (EDTA, acetic acid, other soil amendments) will account for a substantial portion of total costs. Costs for site preparation, i.e., clearing and removal of trees, removal of buildings and debris, etc., would be site-specific and would be in addition to the above cost.

6.1.1 Soil Remediation Time Calculator

The number of crops and time required for phytoremediation to treat a field to a desired cleanup level can easily be estimated. A few basic inputs are required as shown in Table 6-5.

<u>Starting lead concentration</u> (A) - The initial concentration of lead in the soil (400-2000 mg/kg) to be remediated is determined during initial site assessments. The higher the initial lead concentration, the longer the time required to reach a set cleanup goal and the more expensive the process becomes. When the initial lead concentration is too high, then other remediation techniques will be less costly.

<u>Target lead concentration</u> (B) - A cleanup level will be established for a site by agreement with the regulatory agencies. The current industrial cleanup level is 1,000 mg Pb per kg of soil. The current residential cleanup level is 400 mg/kg.

<u>Plant available lead (% of total)</u> (C) - Lead exists in the soil in various forms. Some of the lead compounds can be made available to plants by soil amendments used during phytoextraction, but some of the lead will be inaccessible to the plants even after soil amendment additions. Analysis of the soil lead by sequential extraction with various extractants can identify the fraction of the total lead that is available to the plant during phytoextraction. At TCAAP, the plant available lead was 55% of the total lead. Plant available lead concentrations usually range from 25-75% of total.

Table 6-1
Corn Production and Harvesting Costs[1] Per Crop

Item	Unit Cost	Quantity	Total Cost
Seed	$5/lb	12 lb	$60
Fertilizer[2]	N=$0.24/lb P=$0.25/lb K=$0.14/lb	180 lb N from 341 lb Urea 60 lb P from 130 lb DAP 120 lb K from 200 lb KCl	$70
Fertilizer Application	$15/acre	1 acre	$15
Tillage	$20/acre	1 acre	$20
Planting	$20/acre	1 acre	$20
Harvesting	$20/acre	1 acre	$20
Herbicide and Misc	$25/acre	1 acre	$25
Sampling[3] - Soil - Biomass	$50/sample $50/sample	12 samples 12 samples	$600 $600
Smelting	$100/ton	8 tons	$800
Subtotal			$2,230

(1) Costs are based on typical production agriculture with large scale equipment.
(2) Prices based on bulk quantities. Sources are urea, diammonium phosphate, and potassium chloride.
(3) Unit cost includes labor for collecting samples.

Table 6-2
Extraction Amendment Costs[1] Per Crop

Item	Unit Cost	Quantity at Site C, lb	Quantity Per Acre, lb	Total Cost Per Acre
KOH[2]	$336/ton	1,100	5,900	$990
EDTA[3]	$4,125/ton	1,400	7,500	$15,500
Acetic Acid[4]	$1,520/ton	2,000	10,750	$8,200
KOH and EDTA Mixing	$100/ton EDTA			$375
Acetic Acid Dilution	$100/ton acid			$550
KOH-EDTA Shipping	$40/ton[5]		52,500	$1,050
Acetic Acid Shipping	$30/ton[6]		75,000	$1,130
Labor for Application[7]				$960
Subtotal				$28,755

(1) Based on an initial soil lead concentration of 1,500 mg/kg and a clean-up goal of 1,000 mg/kg.
(2) 45% solution.
(3) Cost per dry ton.
(4) Acid requirement will vary according to site soil.
(5) EDTA makes up about 1/7 of the total weight of the water-KOH-EDTA mixture.
(6) Glacial acetic acid makes up about 1/7 of the diluted mixture.
(7) Based on 16 man-hours at $60 per man-hour.

Table 6-3
Cost Per Crop for Amendment Drip Application/Irrigation System[1]

Item	Unit Cost	Quantity	Total Cost
Drip Tape	$0.03/ft	53,000 ft	$1,590
2-Inch Main	$0.30/ft	300 ft	$90
Filters	$160	4	$640
Flow Regulator	$106	2	$216
Barbs	$0.48	250	$120
Other Plumbing Parts			$200
Installation Cost[2]			$1,280
Subtotal			$4,136

(1) Area to be treated is assumed to be square in shape.
(2) Installation costs based on 32 man-hours at $40 per man-hour.

Table 6-4
Total Cost Per Crop for Phytoextraction of One Acre of Lead-Contaminated Soil to Reduce Soil Lead Content from 1,500 mg/kg to 1,000 mg/kg

Item	Cost
Corn Production and Harvesting Costs	$2,230[1]
Extraction Amendment Costs	$28,755[2]
Cost for Amendment Drip Application/Irrigation System	$4,136[3]
Subtotal of Direct Costs	$35,121
Managing Contractor Fee (20% of direct costs)	$7,024
Total	**42,145**

(1) Subtotal for Table 6-1.
(2) Subtotal for Table 6-2.
(3) Subtotal for Table 6-3.

Table 6-5
Input Required for Calculating the Number of Crops and Number of Years Required to Phytoremediate a One Acre Field

Variable	Units	Input	Range for Inputs
Starting Lead Concentration	mg/kg	A	400 - 2,000
Target Lead Concentration	mg/kg	B	400 (residential), 1,000 (industrial)
Plant Available Lead (% of Total Lead)	%	C	25 - 75
Soil Depth to Remediate	in.	D	1 - 12
Soil Bulk Density (Dry Basis)	lb/cu ft	E	60 - 150
Biomass Production	tons/acre	F	1 - 15
Concentration of Lead in Biomass	%	G	0 - 1 (1% = 10,000 mg/kg)
Number of Crops Per Year	crops/yr	H	1 - 3

Soil depth to remediate (D) - Lead contamination exists to different depths in the soil. The depth of contamination is a factor in determining the total soil volume to be treated. Phytoextraction is more effective and economical when the contamination is shallow, 12 inches or less.

Soil bulk density (dry basis) (E) - Soil density varies substantially depending on the content of clay, sand, and other components. The moisture content also affects the soil density, but this factor can be eliminated by using a dry basis for the soil density. A reasonable value for soil bulk density is 1,600 kg/m^3, which is approximately 100 lb/ft^3.[Ref. 45,46]

Biomass production (F) - Each crop will produce an average weight of biomass (dry basis) per area which normally ranges from 1 to 15 tons per acre. The crop yield is dependent on many factors such as soil fertility, weather conditions during the growing season, length of growing season, number of crops planted per year, presence of toxic compounds in the soil, etc. Crops grown for phytoextraction have amendments applied and are harvested just prior to full maturity. Therefore, the anticipated yields are slightly lower than the published yields. The planting of multiple crops in a single year may shorten the growing time and yield for each crop. The yield may be reduced during subsequent years of phytoremediation due to repeated applications of soil amendments.

Concentration of lead in biomass (G) - There are many factors that affect uptake of the solubilized lead by the crops. The concentration of plant-available lead in the soil directly affects how much lead will be taken up by the crops. Other factors such as root growth, moisture in the soil, rate of amendment application, etc., can influence the lead uptake. Lead concentrations in the plants may range from 0 to 1%.

Crops per year (H) - The number of crops that can be grown in a year is impacted by the climate at the site and the fertility of the soil. A northern U.S. climate may restrict a project to one crop, a southern U.S. climate might allow two crops, and a tropical climate might even allow 3 three crops per year.

The inputs discussed above can be used to calculate the number of crops required to remediate a contaminated field. The calculated values that can be derived are shown in Table 6-6.

Lead to be removed (J) - The requirement for removing lead can be determined by subtracting the *Target lead concentration* from the *Starting lead concentration*. This amount of lead has to be removed from the site to reach the cleanup goal.

$$\text{(J) lb Pb/acre} = \frac{\text{(A-B) mg Pb}}{\text{kg soil}} \left| \frac{2.205 \times 10^{-6}\ \text{lb/mg}}{2.205\ \text{lb/kg}} \right| \frac{\text{E lb soil}}{\text{ft}^3} \left| \frac{43{,}560\ \text{ft}^2}{\text{acre}} \right| \frac{\text{D in.}}{12\ \text{in./ft}}$$

Maximum possible lead removal (K) - Not all of the lead in the soil can be phytoextracted. The lead that can be is based on the percentage of the total lead that is in the plant-available forms. The Maximum possible lead removal can be calculated by multiplying the *Starting lead concentration* (A) by the *Plant available lead (% of total)* (C). If the Lead to be removed (J) is greater than the Maximum possible lead removable (K), then it would be impossible to reach the cleanup level using in situ phytoextraction alone.

$$\text{(K) lb Pb/acre} = \frac{\text{A mg Pb}}{\text{kg soil}} \left| \frac{\text{C \%}}{100\%} \right| \frac{2.205 \times 10^{-6}\ \text{lb/mg}}{2.205\ \text{lb/kg}} \left| \frac{\text{E lb soil}}{\text{ft}^3} \right| \frac{43{,}560\ \text{ft}^2}{\text{acre}} \left| \frac{\text{D in.}}{12\ \text{in./ft}} \right.$$

Table 6-6
Calculated Values for the Number of Crops and Number of Years Required to Phytoremediate a One Acre Field

Calculated Values	Units	Output
Lead to be Removed	lb/acre	J
Maximum Possible Lead Removal	lb/acre	K
Lead Removal Per Crop	lb/acre	L
Number of Crops	crops	M
Number of Years	yr	N

Lead removal per crop (L) - The average amount of lead removed per crop will determine the number of crops required to reach the cleanup level. The crop biomass and the lead removal per crop may potentially decrease over time, but the lead removal per crop is assumed to be constant for the purpose of calculation. The Lead removal per crop is calculated by multiplying the *Biomass production* (F) by the *Concentration of lead in biomass* (G).

$$\text{(L) lb Pb/acre} = \frac{\text{F tons biomass}}{\text{acre}} \left| \frac{2{,}000\ \text{lb}}{\text{ton}} \right| \frac{\text{G \%}}{100\ \%}$$

Number of crops (M) - The number of crops required is calculated by dividing the *Lead to be removed* (J) by the *Lead removal per crop* (L). This calculations assumes that the weather will be cooperative every growing season. A contingency factor could be applied here depending on the meteorological history of the site.

$$\text{(M) Crops} = \frac{\text{J lb Pb/acre}}{\text{L lb Pb/acre}}$$

Number of years (N) - The number of years required to clean up a site with phytoextraction can be calculated by dividing the *Number of crops* (M) by the *Crops per year* (H).

$$\text{(N) Yr} = \frac{\text{M crops}}{\text{H crops/year}}$$

An example calculation is shown below. The values used in this example are based on expected performance of phytoextraction in a southern U.S. area at a site that has fertile soil and weather conducive to growing two crops in a year with no decrease in biomass production during remediation. The inputs are based on lessons learned from the TCAAP demonstration and from information developed from greenhouse studies. The assumed variables for input shown in Table 6-7 provide the calculated outputs shown in Table 6-8.

As shown in Table 6-8, the time required for remediation of the example site would be 14 years. It assumes that 27 crops would be successfully grown with consistent biomass production. The time and costs would be prohibitive under the assumptions shown in Table 6-7 to remediate a field from 1,500 mg/kg to 1,000 mg/kg. Other remediation technologies are available that would be more cost effective. However, if the starting lead concentration was 1,200 mg/kg, then the site could be reduced by 200 mg/kg with 11 crops in 6 years.

Table 6-7
Example Inputs for Calculating the Number of Crops and Number of Years Required to Phytoremediate a Field

Variable	Units	Input	Range for Inputs
Starting Lead Concentration	mg/kg	A=1,500	400 - 2,000
Target Lead Concentration	mg/kg	B=1,000	400 (residential), 1,000 (industrial)
Plant Available Lead (% of Total Lead)	%	C=55	25 - 75
Soil Depth to Remediate	in.	D=12	1 - 12
Soil Bulk Density (Dry Basis)	lb/cu ft	E=100	60 - 150
Biomass Production	tons/acre	F=8	1 - 15
Concentration of Lead in Biomass	%	G=0.50	0 - 1 (1% = 10,000 mg/kg)
Number of Crops Per Year	crops/yr	H=2	1 - 3

Table 6-8
Example Calculated Values for the Number of Crops and Number of Years Required to Phytoremediate a Field

Calculated Values	Units	Output
Lead to be Removed	lb/acre	J=2,178
Maximum Possible Lead Removal	lb/acre	K=3,594
Lead Removal Per Crop	lb/acre	L=80
Number of Crops	crops	M=27
Number of Years	yr	N=14

The calculated values for the example inputs shown in Table 6-7 are:

Lead to be Removed (J) = (A-B) x 10^6 x E x 43,560 x D/12
= (1,500-1,000) x 10^6 x 100 x 43,560 x 12/12
= 2,178 lb/acre

Maximum Possible Lead Removed (K) = A x C/100 x 10^6 x E x 43,560 x D/12
= 1,500 x 55/100 x 10^6 x 100 x 43,560 x 12/12
= 3,594 lb/acre

Lead Removal Per Crop (L) = F x 2,000 x G/100
= 8 x 2,000 x 0.50/100 = 80 lb/acre

Number of Crops (M) = J/L = 2,178/80 = 27 crops

Number of Years (N) = M/H = 27/2 = 14 years

Based on the results of this demonstration, TVA estimated the cost for phytoextraction of one acre to a depth of one foot to be $42,145 per crop, assuming:

- The starting lead concentration is 1500 mg/kg.
- The clean-up goal is 1000 mg/kg.
- Plant-available lead is 55% of the total lead.
- The biomass production is 8 tons per acre.
- The concentration of lead in the biomass is 0.5%.
- Two crops per year are grown at the site.

The cost is equivalent to $26.13 per cubic yard per crop. This remediation would require 27 crops over a period of 14 years, for a total cost of $706 per cubic yard. All other assumptions remaining constant, if the initial soil lead concentration were 1200 mg/kg, the remediation would require 11 crops over a six-year period, at an approximate cost of $287 per cubic yard.

Based on these costs, *in situ* phytoextraction as a sole technology would be economical only when the initial lead concentration is close to the clean-up goal. Costs for site preparation, i.e., clearing and removal of trees, removal of buildings and debris, etc., would be site-specific and would be in addition to the above cost. The total cost includes a managing contractor fee of 20% of the direct costs.   Reagent costs (EDTA, acetic acid, other soil amendments) will account for a substantial portion of total costs.